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Constitutive models for high-temperature flow behaviors of a Ni-based superalloy

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ABSTRACT

The high-temperature deformation behaviors of a typical Ni-based superalloy are investigated by hot compression tests under the strain rate of 0.001–1 s^{-1} and temperature of 920–1040 °C. The experimental results show that the deformation behaviors of the studied superalloy are significantly affected by the deformation temperature, strain rate and strain. The flow stress increases with the increase of strain rate or the decrease of deformation temperature. The flow stress firstly increases with the strain to a peak value, showing the obvious work hardening behaviors. Then, the stress decreases with the further straining, indicating the dynamic flow softening behaviors. Considering the coupled effects of deformation temperature, strain rate and strain on the hot deformation behaviors of the studied Ni-based superalloy, the phenomenological constitutive models are established to describe the work hardening-dynamic recovery and dynamic softening behaviors. In the established models, the material constants are expressed as functions of the Zener–Hollomon parameter. The established constitutive models can give good correlations with the experimental results, which confirm an accurate and precise estimation of the flow stress for the studied Ni-based superalloy.

1. Introduction

During the hot forming process, the high-temperature deformation behaviors of metals and alloys are very complex [1,2]. On the one hand, the hot deformation behaviors are significantly influenced by the thermo-mechanical parameters, such as deformation temperature, strain rate and strain [3–5]. On the other hand, the working hardening [6,7], dynamic recovery and recrystallization [8,9] happen during the hot deformation, which result in the complex microstructural evolution and simultaneously affect the plastic deformation behaviors of metals and alloys [10,11]. Therefore, understandings of the high-temperature deformation behaviors of metals and alloys are very important for designers of hot forming processes to improve the mechanical properties of products [12,13].

In order to obtain the optimal hot forming processing parameters of metals and alloys, considerable efforts have been made on their high-temperature deformation behaviors by a series of experiments, such as hot compression, tension and torsion tests [1,14]. Based on the experimental results, some constitutive models are proposed to accurately describe the plastic deformation characteristics of metals and alloys, and these constitutive models are critical for the correct numerical simulation and the reasonable optimization of hot forming process [1,15]. Based on the recent researches, Lin and Chen [1] presented a critical review on constitutive descriptions for metals and alloys under hot working, and they divided the constitutive models into three categories, including the phenomenological models [16–48], physically-based models [49–53] and artificial neural network models [54–58]. Considering the effects of strain on material constants, Lin et al. [16] proposed a revised hyperbolic sine constitutive equation to describe the high-temperature deformation behaviors of 42CrMo steel. Also, some similar phenomenological models were proposed to predict the plastic deformation behaviors of the commercial purity aluminum [17] and aluminum alloys (2124-T851 aluminum alloy [18], cast A356 aluminum alloy [19], spray-deposited Al–Zn–Mg–Cu alloy [20], Al–Zn–Mg–Zr alloy [21], Al–3Cu–0.5Sc alloy [22], and 6061 aluminum alloy [23]), magnesium alloys (AZ61 magnesium alloy [24] and as-cast AZ80 magnesium alloy [25]), steels (Aermet 100 steel [26], B1500HS steel [27], T24 ferritic steel [28], as-cast 21Cr economical duplex stainless steel [29], GCr15 steel [30],

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A286 iron-base superalloy [31], Sanicro-28 super-austenitic stainless steel [32], and 9Cr–1Mo steel [33,34]), commercially pure titanium (CP–Ti) [35] and Ti-based alloys (Ti–6Al–4V alloy [36] and Ti–6Al–7Nb alloy [37]). On analysis of the test data, Cui et al. [38] proposed the cubic piecewise functions of strain to ensure the high precision of Arrhenius-type hyperbolic sine model. Guo et al. [39] established the modified Voce type model and Arrhenius-type equation to describe the hot deformation behavior of 3003 aluminum alloy. Considering the coupled effects of strain, strain rate and forming temperature on the hot deformation behaviors of Al–Zn–Mg–Cu and Al–Cu–Mg alloys, Lin et al. [40–43] proposed new phenomenological constitutive models to describe the thermo-viscoplastic response of Al–Zn–Mg–Cu and Al–Cu–Mg alloys under hot working condition. In their proposed models, the material constants are presented as functions of strain rate, forming temperature and strain. Also, some modified Johnson–Cook model were established to predict the hot deformation behaviors of 20CrMo alloy steel [44], 42CrMo steel [45], boron steel sheet [46], Ti–6Al–4V alloy [47], and titanium matrix composites [48]. Based on the classical stress–dislocation relation and the kinetics of dynamic recrystallization, the physically-based constitutive equations were established to describe the work hardening–dynamic recovery and dynamic recrystallization behaviors of 42CrMo steel [49], typical superalloys [50,51], as-cast 21Cr economical duplex stainless steel [52], and 55SiMnMo bainite steel [53]. In addition, a number of researchers developed some artificial neural network constitutive models to predict the high-temperature flow behaviors of 42CrMo steel [54], as-cast Ti–6Al–2Zr–1Mo–1V alloy [55], A356 aluminum alloy [56], as-cast Ti60 titanium alloy [57], and 12Cr3WV steel [58].

Due to excellent high temperature characteristics, good fatigue and corrosion resistance, Ni-based superalloys are widely applied in aerospace and energy industries [50,51,59]. The comprehensive investigations of the high-temperature deformation behaviors are particularly important due to the narrow deformation temperature range and large deformation resistance of Ni-based superalloys [60]. Wang et al. [61] studied the effects of δ phase on DRX behaviors of GH4169 alloy during hot compression deformation, and found that the evolution of δ phase is sensitive to the deformation temperature and strain rate. Lin et al. [62,63] studied the hot tensile deformation behaviors and fracture characteristics of a typical Ni-based superalloy (GH4169), and found that the typical DRX characteristics appear under relatively high deformation temperatures (1010 and 1040 °C). Also, δ phase (Ni_3Nb) can cause the obvious work hardening at the beginning of hot deformation, and then accelerates the flow softening by promoting the dynamic recrystallization with further straining. With the increase of initial δ phase, the strain rate sensitivity coefficient decreases firstly and then increases. Meanwhile, the increase of initial δ phase increases the density of nucleus for the formation of microvoids, and promotes the nucleation and coalescence of microvoids. Wen et al. [64] established the processing map to optimize the hot working processing for a typical Ni-based superalloy (GH4169), and found that the changes of instability domains may be related to the evolution of δ phase during hot deformation. Wang et al. [66] found that the existence of δ phase can lead to an increase of strain rate sensitivity exponent and activation energy of GH4169 superalloy. Additionally, the high-temperature deformation behaviors of Ni-based superalloys were also studied by Yao et al. [66], Sun et al. [67], Etaati et al. [68], Ning et al. [69], etc. Although some studies have been conducted to investigate the high-temperature deformation behaviors of Ni-based superalloys, the constitutive models are still not advanced enough to account for the whole complex dynamic mechanisms.

In this study, the high-temperature deformation behaviors of a typical Ni-based superalloy with δ phase (Ni_3Nb) are investigated by hot compression tests under the wide ranges of deformation temperature and strain rate. The phenomenological constitutive models are established to describe the coupled effects of deformation temperature, strain rate, and strain on the high-temperature deformation behaviors of the studied Ni-based superalloy.

2. Experiments and results

A typical Ni-based superalloy with compositions (wt%) of 52.82Ni–18.96Cr–5.23Nb–3.01Mo–1.00Ti–0.59Al–0.01Co–0.03C–(bal.) Fe was used in this study. The metastable body-centered tetragonal coherent precipitate γ'' phase (Ni_3Nb) and the face-centered cubic coherent precipitate γ' phase (Ni_3Al) are the strengthening phases. Furthermore, γ'' is the major strengthening phase which may transform to δ phase (Ni_3Nb) in equilibrium [60–65]. Cylindrical specimens were machined with a diameter of 8 mm and a height of 12 mm. The heat treatment processes consist of two steps, i.e., the specimens were firstly homogenized under 1040 °C for 45 min, and then aged under 900 °C for 9 h. Each step was followed by water quenching. The microstructure after the heat treatment is shown in Fig. 1. According to the standard ASTM: E112-12, the average grain size was evaluated as about 75 μm by the linear intercept method. The hot compression tests were conducted on Gleeble-3500 thermo-simulation machine under the strain rate of 0.001–1 s^{-1} and the deformation temperature of 920–1040 °C. The specimens were firstly heated to the deformation temperature at the heating rate of 10 °C/s, and held for 5 min to eliminate the thermal gradient before loading. Then, the specimens were compressed with the deformation degree of 70%, and immediately quenched by water after the hot deformation.

The typical true stress–true strain curves of the studied Ni-based superalloy obtained from the hot compression tests are shown in Fig. 2. Obviously, the flow stresses are sensitive to the deformation temperature, strain rate and strain. The stress increases with the decrease of deformation temperature or the increase of strain rate. The true stress–true strain curves exhibit a peak stress at a small strain, after which the flow stresses decrease monotonically till high strains, showing the dynamic softening. Under high deformation temperatures or low strain rates, the flow stress reaches a steady stage with further straining, whereas it decreases monotonically under the low deformation temperatures or high strain rates.

As shown in Fig. 3, the typical true stress–true strain curve usually consists of four different stages, i.e., work hardening stage (Stage I), stable stage (Stage II), softening stage (Stage III) and steady stage (Stage IV) [49]. However, for the studied Ni-based

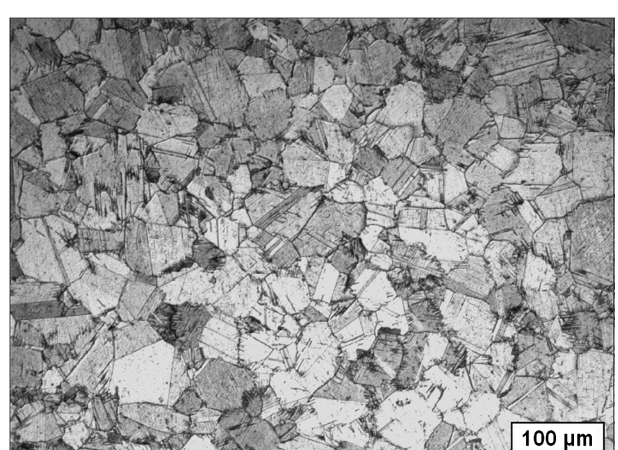

Fig. 1. Optical microstructure of the studied superalloy before hot deformation.